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Measurement of the  $k_{\mathrm{t}}$  splitting scales in  $Z \rightarrow \ell\ell$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector

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# Measurement of the $k_t$ splitting scales in $Z \rightarrow \ell\ell$ events in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector



## The ATLAS collaboration

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**ABSTRACT:** A measurement of the splitting scales occurring in the  $k_t$  jet-clustering algorithm is presented for final states containing a  $Z$  boson. The measurement is done using  $20.2\text{ fb}^{-1}$  of proton-proton collision data collected at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV by the ATLAS experiment at the LHC in 2012. The measurement is based on charged-particle track information, which is measured with excellent precision in the  $p_T$  region relevant for the transition between the perturbative and the non-perturbative regimes. The data distributions are corrected for detector effects, and are found to deviate from state-of-the-art predictions in various regions of the observables.

**KEYWORDS:** Hadron-Hadron scattering (experiments)

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**1 Introduction**

A collimated spray of particles arising from a cascade of strong interactions is commonly referred to as a hadronic jet. Jet production in association with other final-state particles can constitute signal as well as an important background process in many of the precision measurements and new-physics searches conducted at CERN's Large Hadron Collider (LHC). A good understanding of processes initiated by strong interactions is therefore crucial.

Jet production in association with a leptonically decaying heavy gauge boson ( $V = W, Z$ ) allows effects of the strong interaction to be studied in a relatively clean environment. Good progress has been made in recent years towards higher-order calculations of these processes in quantum chromodynamics (QCD), e.g. fixed-order calculations of high jet multiplicities at next-to-leading order (NLO) [1, 2] and the inclusive as well as  $V + 1$ -jet processes at next-to-next-to-leading order (NNLO) [3]. Furthermore, new methods have

been published for matching NLO  $V + \text{multijet}$  predictions with the parton shower in a merged sample [4–6], or to match NNLO calculations to a parton shower for the inclusive processes [7, 8]. Comparisons of precision measurements to these accurate predictions are a powerful means by which to study aspects of QCD.

While properties of the jets can be studied directly using the jet momenta, a complementary approach is taken in this paper by studying the jet production rates at different resolution scales. To this end, splitting scales of jets are constructed using an infrared-safe clustering algorithm based on sequential combination of the input momenta. In this analysis the  $k_t$  algorithm [9, 10] is used, with distance measures defined for every iteration as follows:

$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \times \frac{\Delta R_{ij}^2}{R^2}, \quad (1.1)$$

$$d_{ib} = p_{T,i}^2, \quad (1.2)$$

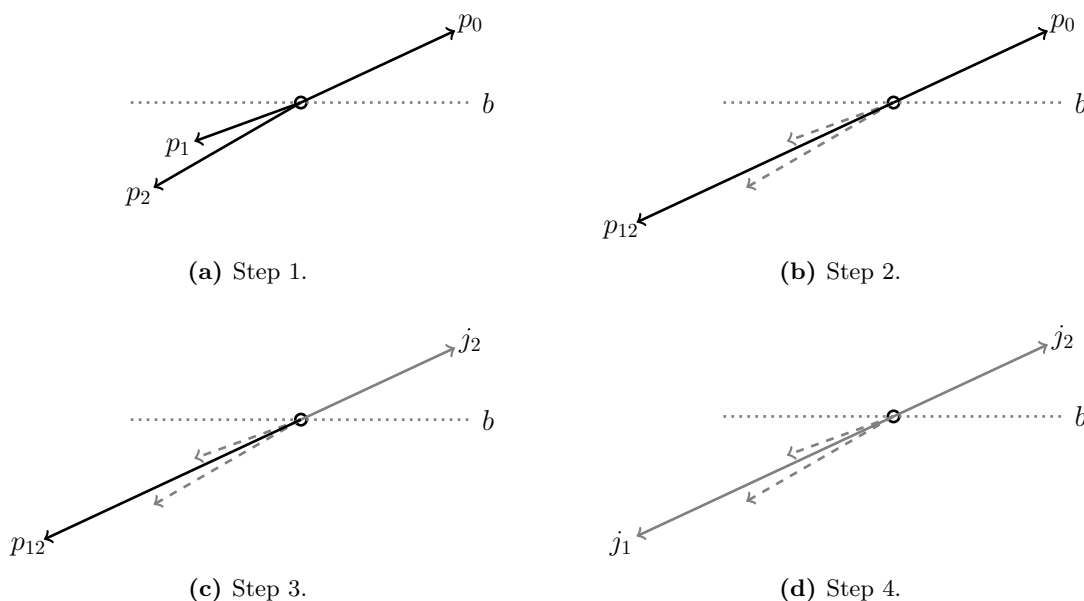
where the transverse momentum  $p_T$  carries an index corresponding to the  $i^{\text{th}}$  and  $j^{\text{th}}$  constituent momentum in the input list, for all possible permutations of  $i$  and  $j$  in the given clustering step. The input momenta separation  $\Delta R_{ij}$  is defined in terms of the rapidity  $y$  and the azimuthal angle  $\phi$  via the relation  $(\Delta R_{ij})^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ . The index  $b$  denotes the beam line and the parameter  $R$  governs the average cone size in  $y$ – $\phi$  space around the jet axis. For a given iteration of the algorithm in which the number of input momenta drops from  $k + 1$  to  $k$ , the associated squared splitting scale  $d_k$  is given by the minimum of all the  $d_{ij}$  and  $d_{ib}$  scales defined for that iteration step:

$$d_k = \min_{i,j}(d_{ij}, d_{ib}). \quad (1.3)$$

If this minimum is a  $d_{ij}$ , the  $i^{\text{th}}$  and  $j^{\text{th}}$  momenta in the input list are replaced by their combination. If the minimum is a  $d_{ib}$ , the  $i^{\text{th}}$  momentum is removed from the input collection and is declared a jet. The index  $k$  defines the order of the splitting scale, with  $k = 0$  being the last iteration step before the algorithm terminates. Hence the zeroth-order splitting scale,  $\sqrt{d_0}$ , corresponds to the  $p_T$  of the leading  $k_t$ -jet, and one can regard the  $N^{\text{th}}$  splitting scale,  $\sqrt{d_N}$ , as the distance measure at which an  $N$ -jet event is resolved as an  $(N + 1)$ -jet event. The steps of a  $k_t$  clustering sequence using three input momenta are illustrated in figure 1.

In this paper, measurements of differential distributions of the splitting scales occurring in the  $k_t$  clustering algorithm using charged-particle tracks in events with  $Z + \text{jets}$  are presented. The aim is to constrain the theoretical modelling of strong-interaction effects, and charged-particle tracks are used instead of calorimeter cells to reduce the systematic uncertainties of the measurements significantly. In addition to these primary results using only charged-particle information, less precise extrapolated results including neutral particles are also provided to allow comparisons to fixed-order calculations.

The measurements are performed independently in the  $Z \rightarrow e^+e^-$  and  $Z \rightarrow \mu^+\mu^-$  decay channels as well as for jet-radius parameters of  $R = 0.4$  and  $R = 1.0$  in each decay channel. The presented analysis is complementary to the ATLAS measurement of the  $k_t$  splitting scales in  $W + \text{jets}$  events at  $\sqrt{s} = 7 \text{ TeV}$  [11].



**Figure 1.** Simplified illustration of the  $k_t$  clustering algorithm, starting with three input momenta  $p_0$ ,  $p_1$  and  $p_2$  (step 1). The dotted line labelled  $b$  represents the beam line. In step 2, the minimum distance measure is the one between two input momenta  $p_1$  and  $p_2$ , so that the two input momenta are replaced by their vector combination. In step 3, the minimum distance measure is between the  $p_0$  and the beam line, so that  $p_0$  is declared a jet ( $j_2$ ) and removed from the input list. Finally in step 4, there is only the combined input momentum  $p_{12}$  left and so it will be declared a jet ( $j_1$ ) and the algorithm terminates.

## 2 ATLAS detector

The ATLAS detector is described in detail in ref. [12]. Tracks and interaction vertices are reconstructed with the inner detector (ID) tracking system, consisting of a silicon pixel detector, a silicon microstrip detector (SCT) and a transition radiation tracker. The ID is immersed in a 2 T axial magnetic field, providing charged-particle tracking in the pseudorapidity range  $|\eta| < 2.5$ .<sup>1</sup> The ATLAS calorimeter system provides fine-grained measurements of shower energy depositions over a wide range of  $\eta$ . An electromagnetic liquid-argon sampling calorimeter covers the region  $|\eta| < 3.2$  and is divided into a barrel part ( $|\eta| < 1.475$ ) and an endcap part ( $1.375 < |\eta| < 3.2$ ). The hadronic barrel calorimeter ( $|\eta| < 1.7$ ) consists of steel absorbers and active scintillator tiles. The hadronic endcap calorimeter ( $1.5 < |\eta| < 3.2$ ) and forward electromagnetic and hadronic calorimeters ( $3.1 < |\eta| < 4.9$ ) use liquid argon as the active medium. The muon spectrometer comprises separate trigger and high-precision tracking chambers measuring the deflection

<sup>1</sup>ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

of muons in a magnetic field generated by superconducting air-core toroids. The precision chamber system covers the region  $|\eta| < 2.7$  with three layers of monitored drift tube chambers, complemented by cathode strip chambers in the forward region. The muon trigger system covers the range  $|\eta| < 2.4$  with resistive plate chambers in the barrel, and thin gap chambers in the endcap regions. A three-level trigger system is used to select events of interest [13]. The Level-1 trigger reduces the event rate to less than 75 kHz using hardware-based trigger algorithms acting on a subset of the available detector information. Two software-based trigger levels then reduce the event rate further to about 400 Hz using the complete detector information.

### 3 Event selection

The measurement is performed using proton-proton collision data recorded at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV. The data were collected between April and December 2012 in data-taking periods where the detector was fully operational, resulting in an integrated luminosity of  $20.2 \text{ fb}^{-1}$ .

#### 3.1 Object reconstruction and event selection at detector level

Events containing a dilepton candidate were retained for further analysis using dedicated triggers requiring the presence of two oppositely charged electrons with transverse momentum above 12 GeV or two oppositely charged muons with transverse momenta above 18 GeV and 8 GeV respectively.

Inner detector tracks are selected in the phase-space region  $p_T > 400$  MeV and  $|\eta| < 2.5$ . The track candidates are required to have at least one hit in the pixel detector and at least five SCT hits. A hit in the innermost pixel layer is required in cases where the track candidates have passed through an active region of that layer. The track reconstructed from the hits is then extrapolated and combined with information from the transition radiation tracker [14]. The reduced  $\chi^2$  of the track fit is required to be less than 3 in order to remove mismeasured tracks or combinatorial background. In order to reject backgrounds stemming from other proton-proton collisions in the same or different bunch crossings (pileup), the transverse and longitudinal impact parameters are required to be  $|d_0| < 1.0$  mm and  $|z_0 \times \sin \theta| < 0.6$  mm with respect to the primary vertex, respectively. The primary vertex in the event is defined as the collision vertex with the highest sum of squared transverse momenta of the associated ID tracks.

Electron candidates are identified as clusters of energy in the electromagnetic calorimeter which are associated with a corresponding ID track. They are required to have  $p_T > 25$  GeV and  $|\eta| < 2.47$ , excluding the transition regions between the barrel and endcap electromagnetic calorimeters ( $1.37 < |\eta| < 1.52$ ). The electron candidates must satisfy a set of *medium* selection criteria [15] that have been optimised for the high rate of proton-proton collisions per beam crossing observed in the 2012 data. Electron candidates are required to be isolated, meaning that the scalar sum of the  $p_T$  of those tracks within  $\Delta R = 0.2$  around the electron track is required to be less than 13% of the  $p_T$  of the electron. (The definition of  $\Delta R$  is the same as for the  $k_t$  algorithm, except that it makes

use of pseudorapidity rather than rapidity.) Impact parameter requirements are imposed to ensure that the electron candidates originate from the primary vertex.

Muon candidates are reconstructed using the *combined muon* algorithm [16], which involves matching and combining ID tracks with tracks in the muon spectrometer. The muon candidates are required to have  $p_T > 25$  GeV and  $|\eta| < 2.4$ . Muon track quality requirements are imposed to suppress backgrounds, along with impact parameter requirements to ensure that the muon candidates originate from the primary vertex. Muon candidates are also required to be isolated, meaning that the scalar sum of the  $p_T$  of those tracks within  $\Delta R = 0.2$  around the muon track (using pseudorapidity again) is required to be less than 10 % of the  $p_T$  of the muon.

A  $Z$ -boson candidate is selected by requiring exactly two opposite-charge same-flavour leptons (electrons or muons) and requiring the invariant mass of the dilepton system to satisfy  $71 \text{ GeV} < m_{\ell\ell} < 111 \text{ GeV}$ . The momenta of all selected ID tracks – apart from the two lepton tracks – are then passed into the  $k_t$  clustering algorithm introduced in section 1 to construct the splitting scales.

### 3.2 Particle-level selection and phase-space definition

Particle-level predictions are obtained using final-state objects with a mean decay length ( $c\tau$ ) longer than 10 mm. Leptons are defined at the dressed level, i.e. they are given by the four-momentum combination of the respective lepton (an electron or a muon) and all nearby photons within a cone of size  $\Delta R = 0.1$  centred on the lepton. Electrons are required to pass  $|\eta| < 2.47$ , excluding the transition region between the barrel and end cap electromagnetic calorimeters  $1.37 < |\eta| < 1.52$ , whilst muons are selected with  $|\eta| < 2.4$ . Furthermore, a transverse momentum requirement of  $p_T > 25$  GeV is imposed for either lepton flavour.

Events are required to contain a  $Z$ -boson candidate, defined as exactly two oppositely charged, same-flavour leptons (electrons or muons) with a dilepton invariant mass of  $71 \text{ GeV} < m_{\ell\ell} < 111 \text{ GeV}$ .

All *charged* final-state particles with  $p_T > 400$  MeV and  $|\eta| < 2.5$  — excluding the selected leptons — serve as input to the  $k_t$  clustering algorithm to construct the splitting-scale observables. The measurement is performed twice, using jet-radius parameters of 0.4 and 1.0 respectively. This allows studies of the resolution scales of both narrow and broad jets, which have different sensitivity to the hadronisation and underlying-event modelling.

## 4 Monte Carlo simulation

### 4.1 Samples of simulated events

Signal event samples for  $Z \rightarrow e^+e^-$  and  $Z \rightarrow \mu^+\mu^-$  production in association with jets (QCD  $Z + \text{jets}$ ) were generated in order to correct the data for detector effects in an unfolding procedure and to estimate systematic uncertainties. The samples were produced using the SHERPA v1.4.3 and POWHEG-BOX [17–19] (SVN revision r1556) event generators. The SHERPA samples are based on matrix elements with up to four additional hard

emissions at leading order (LO), using parton distribution functions (PDFs) from the CT10 set [20], which were matched and merged to the SHERPA parton shower using the set of tuned parameters developed by the SHERPA authors. The POWHEG-BOX samples (hereafter referred to as the POWHEG samples) use the CT10 PDF set and are passed through PYTHIA v8.175 and subsequently through PHOTOS++ [21] for parton showering and radiative quantum-electrodynamical corrections, respectively.

$Z \rightarrow \tau^+\tau^-$  as well as  $W + \text{jets}$  production were generated with SHERPA using the MENLOPS prescription [22] to merge the results of inclusive  $Z \rightarrow \tau^+\tau^-$  and  $W \rightarrow \ell\nu$  calculations performed at NLO accuracy with the LO multi-leg prediction. All QCD  $V + \text{jets}$  samples are normalised using an inclusive NNLO cross section [23].

Processes involving matrix elements with up to one additional parton emission for electroweak  $Z + \text{jets}$  production (including all diagrams with three electroweak couplings at tree level) were simulated using SHERPA. The background contribution from  $WW$  production with both bosons decaying leptonically is estimated using POWHEG+PYTHIA 8.

Background contributions stemming from top-quark interactions ( $t\bar{t}$ ,  $t$ -channel single top and  $Wt$ ) were generated using POWHEG with the CT10 PDF set in the hard scattering in conjunction with PYTHIA v6.427 [24] for parton showering and hadronisation using the CTEQ6L1 [25] PDF set and the corresponding Perugia 2011C [26] set of tuned parameters. The `hdamp` parameter, which controls the  $p_T$  of the first additional emission beyond the Born configuration, is set to the mass of the top quark. The  $t\bar{t}$  sample is normalised using a NNLO calculation in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms [27], while the single-top samples are normalised using an approximate NNLO calculation including NNLL-accurate resummation of soft gluon terms [28–30].

The Monte Carlo event samples mentioned above were passed through GEANT4 [31, 32] for a full simulation [33] of the ATLAS detector and are reconstructed with the same analysis chain as used for the measured data. Pileup is simulated with PYTHIA v8.175 [34] using the A2 [35] set of tuned parton shower parameters and the MSTW2008lo [36] set of parton distribution functions.

## 4.2 Theoretical predictions

In addition to the samples of fully simulated events, additional particle-level predictions were generated to provide a state-of-the-art comparison to the unfolded measurements.

Predictions for  $Z$  boson production in association with jets are obtained using the SHERPA v2.2.1 generator [37]. Matrix elements are calculated for up to two additional parton emissions at NLO accuracy and up to four additional parton emissions at LO accuracy using the Comix [38] and OPENLOOPS [39] matrix element generators, and merged with the SHERPA parton shower [40] which is based on Catani-Seymour subtraction terms. The merging of multi-parton matrix elements with the parton shower is achieved using an improved CKKW matching procedure [41, 42], which is extended to NLO accuracy using the MEPS@NLO prescription [4]. The PDFs are provided by the NNPDF3.0nnlo set [43] and the dedicated set of tuned parton shower parameters developed by the SHERPA authors is used.



Process	$Z \rightarrow e^+e^-$		$Z \rightarrow \mu^+\mu^-$	
	Events	Contribution [%]	Events	Contribution [%]
QCD $Z$ + jets	5 090 000	98.93 %	7 220 000	99.40 %
Multijet	42 000	0.81 %	25 000	0.34 %
Electroweak $Z$ + jets	5 350	0.10 %	7 340	0.10 %
Top quarks	6 190	0.12 %	8 440	0.12 %
$W(W)$	1 100	0.02 %	1 460	0.02 %
$Z \rightarrow \tau^+\tau^-$	1 100	0.02 %	1 700	0.02 %
Total expected	5 150 000	100.00 %	7 260 000	100.00 %
Total observed	5 196 858		7 349 195	

**Table 1.** Observed and expected numbers of events in the electron and the muon channels. The signal as well as the electroweak  $Z$  + jets,  $WW$ ,  $W$  + jets,  $t\bar{t}$  and single-top background rates are estimated using dedicated Monte Carlo samples. The multijet background is estimated using a data-driven technique.

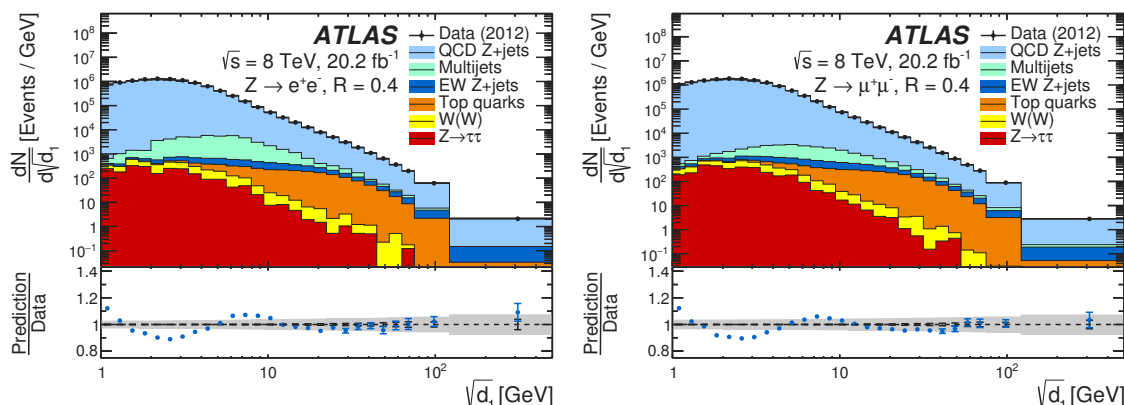
Predictions for  $Z$  + jets production at NNLO were provided by the DY@NNLOPS authors [8]. The calculations are obtained using DYNNLO [44, 45] along with the multi-scale improved NLO (MiNLO) prescription [46] for the scale choices as implemented in the POWHEG-BOX package [19, 47]. For the hard scattering the PDF4LHC15nnlo PDF set [48] is used, and parton showering is provided by PYTHIA v8.185 using the Monash [49] set of tuned parameters.

## 5 Analysis method

Distributions of the  $k_t$  splitting scales up to the seventh order were constructed from track momenta selected according to section 3.1.

### 5.1 Background estimation

Events from the signal process and the background contributions from  $Z \rightarrow \tau^+\tau^-$ ,  $W$  + jets, top-quark pair and single top quark production as well as diboson and electroweak  $Z$  + jets production are obtained by applying the analysis chain to the dedicated simulated samples introduced in section 4.1. The multijet background can also contribute if two jets are misidentified as leptons or if they contain leptons from  $b$ - or  $c$ -hadron decays. A multijet-enhanced sample is obtained from the data by reversing some of the lepton identification criteria. A two-component template fit to the dilepton invariant mass spectrum is then employed to determine the normalisation in the fiducial measurement region, using the multijet template and a template formed from all other processes. Table 1 shows the estimated composition in each lepton channel. The relative sizes of the various background contributions are also illustrated in figure 2, which shows the  $\sqrt{d_1}$  distribution at the detector level in both the electron and the muon channel. The purity of the signal is close to 99 %.



**Figure 2.** Detector-level splitting scale distributions in the electron and muon channels using the jet-radius parameter  $R = 0.4$ . The lower panel shows the ratio of the combined Monte Carlo predictions to the data. The size of the error bars reflects the statistical uncertainty for predictions and data, while the combined experimental and systematic data uncertainty is indicated by a grey band around unity.

## 5.2 Unfolding

The estimated number of background events is subtracted from the data in each bin of a given distribution. The background-subtracted data are then unfolded back to the particle level using an iterative procedure based on Bayes’ theorem [50, 51], which makes use of an unfolding prior that is updated at each iteration. In the first iteration, the nominal particle-level predictions from SHERPA are used as the unfolding prior. The detector resolution causes bin-to-bin migrations, which are corrected for using a detector response matrix in the unfolding procedure. Acceptance and efficiency losses in the fiducial measurement region as well as fake contributions (e.g. due to pileup) are also accounted for. The unfolded bin values are found to converge after five iterations in most cases. The statistical uncertainty in data and simulation is estimated using pseudoexperiments.

In addition to the nominal charged-particle-level results (“*charged-only*”), the unfolding procedure is repeated using particle-level predictions that include the neutral particles as well, thereby extrapolating the data to a particle-level including all particles (“*charged+neutral*”). The requirements on the  $Z$ -boson candidate and the particles entering the clustering sequence remain identical to those of the charged-only analysis. These extrapolated results are provided for the benefit of theoretical calculations which cannot account for hadronisation processes, and depend strongly on the modelling of hadronisation processes in the generator used during the unfolding. Since the extrapolation and the corresponding uncertainty estimate could change with other hadronisation models in the future, the “charged-only” measurements should be considered the primary results of this publication.

## 5.3 Systematic uncertainties

The systematic variations outlined below are propagated through the unfolding procedure by creating a new response matrix constructed from the simulation after reweighting,

smearing or shifting the relevant event weights or objects. The shift in the unfolded spectrum is symmetrised and taken as a systematic uncertainty in the final result. The binning is chosen to be uniform in logarithmic space, with some bins merged towards the tails of the distributions to compensate for statistical fluctuations in the data.

Experimental uncertainties arise from the lepton-based and luminosity systematic uncertainties, the pileup modelling as well as the track reconstruction efficiency. The systematic uncertainties in the lepton reconstruction, identification, isolation and trigger efficiencies, as well as the lepton momentum scale and resolution, are defined in refs. [15, 16]. The total impact of the lepton-based systematic uncertainties on the final results is typically 1 % or less. The uncertainty in the integrated luminosity is 1.9 %, as determined from beam separation scans [52] performed in November 2012. The difference in the pileup profile between the detector-level simulation and the data is corrected for by reweighting the simulation to match the average number of proton-proton collisions observed in the data. The impact of the remaining mismodelling on the measurement is found to be at most 1 %, which is assigned as a systematic uncertainty. The efficiency to reconstruct an ID track depends on the ID material distribution. A corresponding uncertainty is derived by comparing the nominal simulation to a dedicated simulation using a distorted ID geometry and a 15 % increase in the material budget. The resulting systematic uncertainty associated with the track reconstruction efficiency is typically at the level of 5 % but can rise to 10 % in the tails of the distributions, in particular for higher-order splitting scales. Uncertainties associated with the track momentum are found to be negligible for the range of track momenta probed in this measurement. As a cross-check, splitting scales are also constructed in data and simulation using tracks that do not pass the nominal longitudinal impact parameter requirements in order to assess the modelling of pileup and fake tracks in the simulation. Good agreement is observed between data and simulation, with the data being generally described to within 10 %. The differences are covered by the assigned uncertainties, which are larger in that region due to the larger fraction of fake and pileup tracks, and so no additional systematic uncertainties in the pileup modelling or fake-track rates are assigned.

A data-driven uncertainty associated with the imperfect modelling of the unfolded observables at the detector level is obtained by reweighting the simulation such that the level of agreement between the detector-level distributions and the data is improved before performing the unfolding procedure. The reweighting is applied at the particle level using the ratio of the distributions in data and detector-level simulation and results in a systematic uncertainty of at most 5 %. An algorithmic uncertainty associated with the number of iterations chosen in the unfolding procedure is taken to be the difference between the results unfolded using ten iterations and the nominal results obtained using five unfolding iterations. The algorithmic unfolding uncertainty is at the subpercent level.

An uncertainty due to the choice of generator used to unfold the data, which is the dominant systematic uncertainty, is obtained by replacing the nominal SHERPA prediction in the full analysis chain with a prediction from POWHEG+PYTHIA 8, which uses a very different parton shower and hadronisation model compared to the nominal generator. The difference between the results unfolded with the nominal predictions and the alternative

predictions is then symmetrised and assigned as an uncertainty in the choice of unfolding prior. This uncertainty estimate might be reduced by reweighting both SHERPA and POWHEG+PYTHIA 8 to the experimental data at reconstruction level before constructing the response matrices. Since it is not clear that this would still cover the full impact of non-perturbative effects on the unfolding, no such reweighting is applied when assessing the unfolding-prior uncertainty.

The extrapolated “charged+neutral” results are also obtained using the generator combinations described above as unfolding priors, providing an estimate of the extrapolation uncertainty.

To cover further systematic effects of the unfolding algorithm on the extrapolated results, an MC-closure uncertainty was derived by unfolding POWHEG+PYTHIA 8 from detector level to the charged+neutral level using response matrices generated from the SHERPA samples. The difference with respect to the direct charged+neutral predictions from POWHEG+PYTHIA 8 is then added as an MC-based closure uncertainty in analogy to the data-driven reweighting uncertainty described above.

The breakdown of the corresponding systematic uncertainties can be found in figure 3. In the breakdowns, the total uncertainty shown is the full quadrature sum of all the individual statistical and systematic uncertainty components. This includes a constant  $\pm 1.9\%$  uncertainty in the luminosity estimate, which is omitted from the breakdown for clarity. The curve labelled ‘experimental’ contains the tracking and pileup uncertainties as well as the systematic uncertainties associated with the  $Z$ -boson candidate selection. The curve labelled ‘unfolding’ contains the uncertainties associated with the unfolding procedure, namely the unfolding closure uncertainty, the uncertainty associated with the number of iterations as well as the unfolding-prior uncertainty.

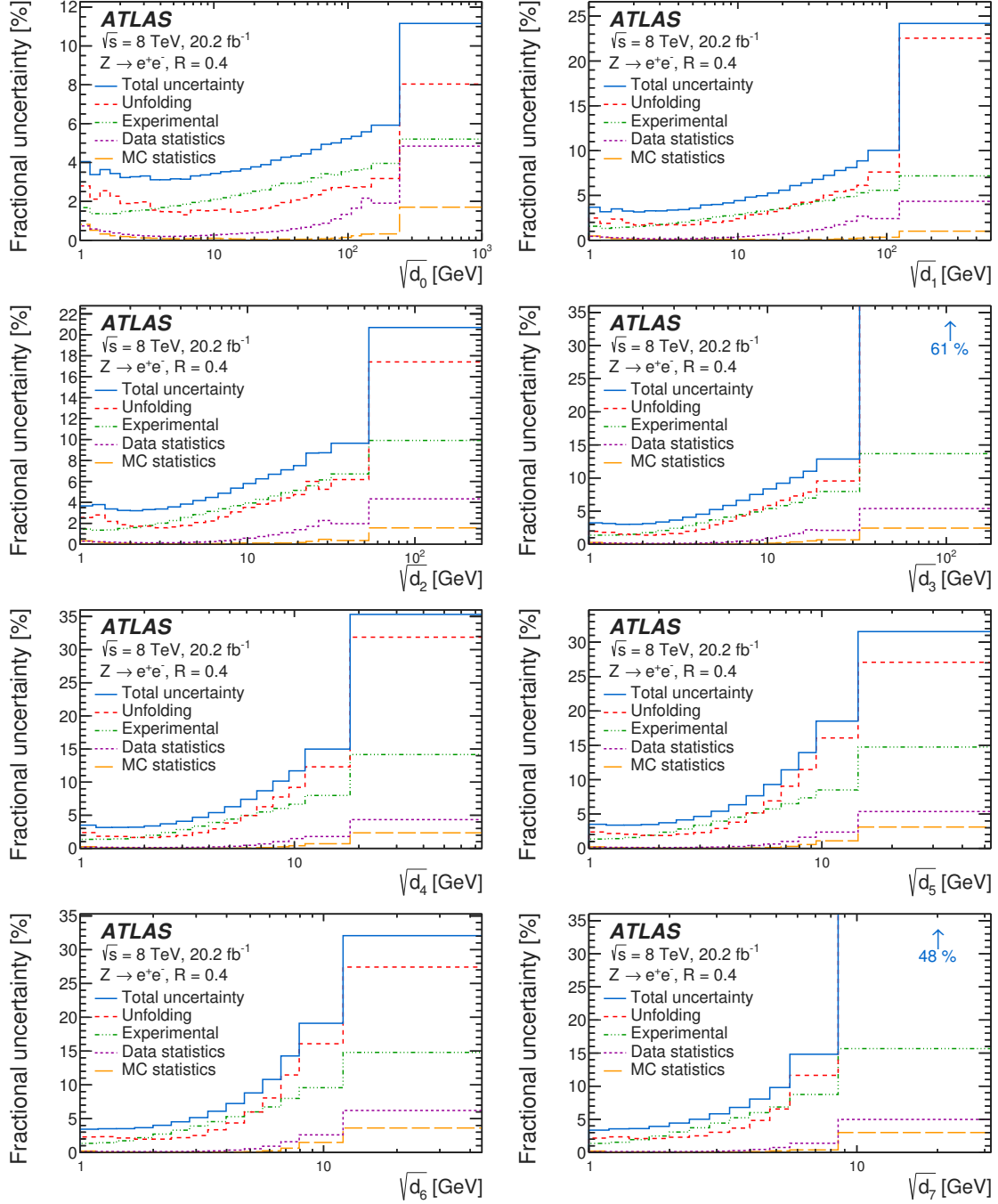
## 6 Results

In this analysis, distributions for eight splitting scales,  $\sqrt{d_0} \dots \sqrt{d_7}$ , are obtained for all combinations of

- two lepton flavours,  $Z \rightarrow e^+e^-$  and  $Z \rightarrow \mu^+\mu^-$ ,
- two radius parameters in the jet algorithm,  $R = 0.4$  and  $R = 1.0$ , and
- two particle-level definitions: “charged-only” and “charged+neutral”, as introduced in section 5.2.

A full set considering all splitting scales is shown only for the electron-channel analysis with  $R = 0.4$  in figure 4, while other combinations can be found in appendices A and B.

The measured differential cross sections are compared to state-of-the-art predictions obtained from SHERPA (‘MEPS@NLO’) and DY@NNLO+POWHEG+PYTHIA 8 (‘NNLOPS’). Details of the respective generator setups are given in section 4.2. PDF uncertainties for the MEPS@NLO prediction are estimated with the NNPDF3.0nnlo [43] replicas using LHAPDF [53]. They are combined with an uncertainty estimate based on



**Figure 3.** Breakdowns of the total systematic uncertainty into its contributions in the electron channel using the jet-radius parameter  $R = 0.4$ . The total uncertainty shown is the full quadrature sum of all the individual statistical and systematic uncertainty components, including a constant  $\pm 1.9\%$  uncertainty in the luminosity estimate.

7-point scale variations, i.e. all combinations of factors of 0.5, 1 and 2 in the factorisation and renormalisation scales are taken into account except the opposite combinations of (0.5, 2) or (2, 0.5). The scale uncertainty envelope for the NNLOPS prediction is obtained from 21-point scale variations using the prescription described in ref. [8].

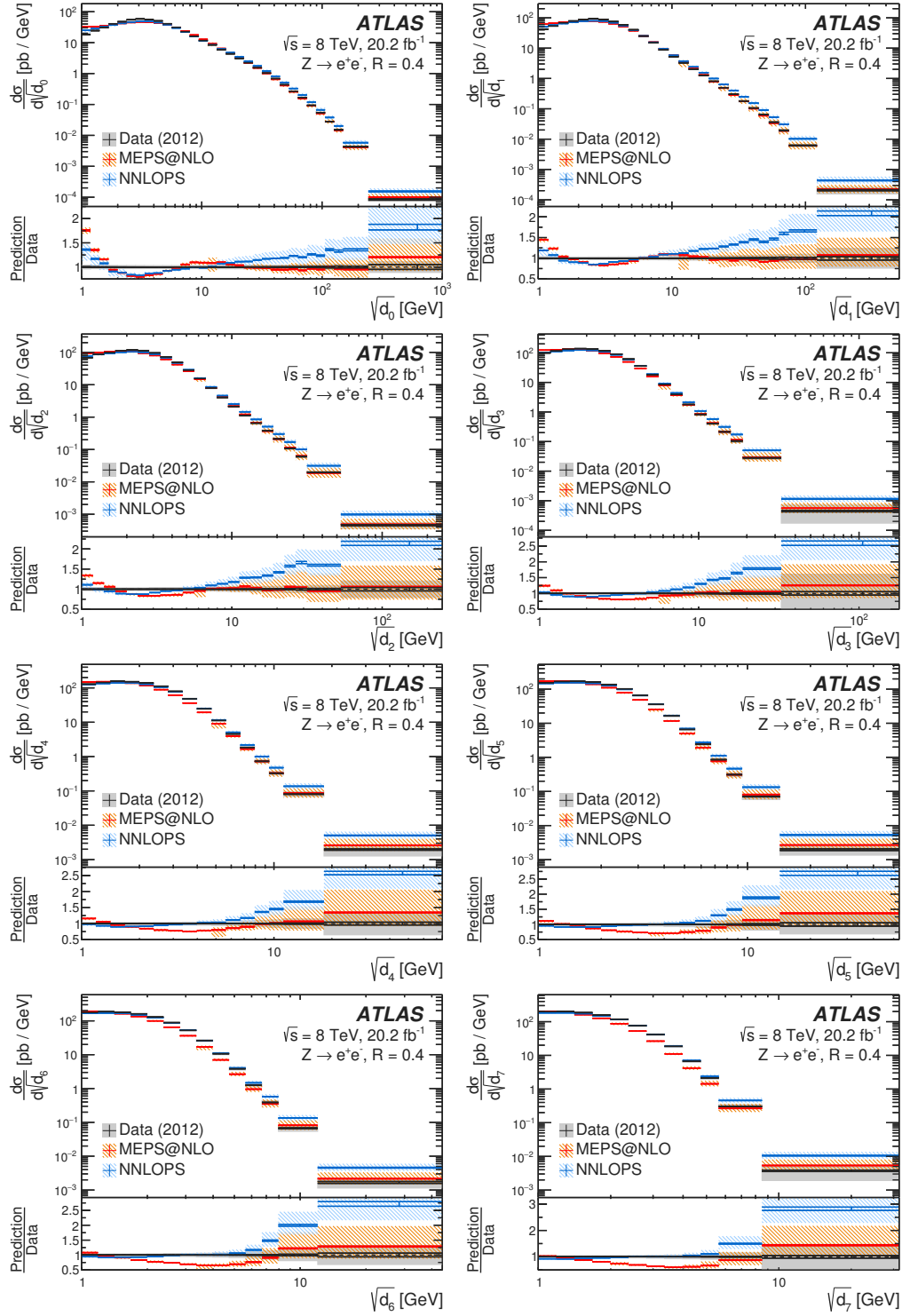
Neither of the generators provides a fully satisfactory description of the experimental data. In the ratio plots of the lower-order splitting scales it is seen that both predictions underestimate the cross section in the peak region at values of around 3 GeV by typically 10–20%, but are consistent with the data at 10 GeV. At higher values the MEPS@NLO prediction agrees well with the data while the NNLOPS prediction systematically overestimates the cross section. Both overshoot the data significantly in the region close to 1 GeV. The level of agreement of the NNLOPS predictions in the soft region is improved significantly for the higher-order splitting scales.

The generator uncertainties in these comparisons are only estimated by varying parameters related to the perturbative aspects of the MC generators. In the soft region of the splitting-scale distributions other aspects become relevant, such as hadronisation and multiple parton interactions, and even the parton shower modelling. The discrepancies unveiled by these measurements indicate that the data can provide new input for the tuning of parameters in the non-perturbative stages of event generators.

Figure 5 displays again the first-order splitting scale,  $\sqrt{d_1}$ , to demonstrate the different variations in the analysis due to the choice of lepton flavour, jet-radius parameter and particle level. A detailed breakdown of the systematic uncertainties is included here in the same style as described earlier.

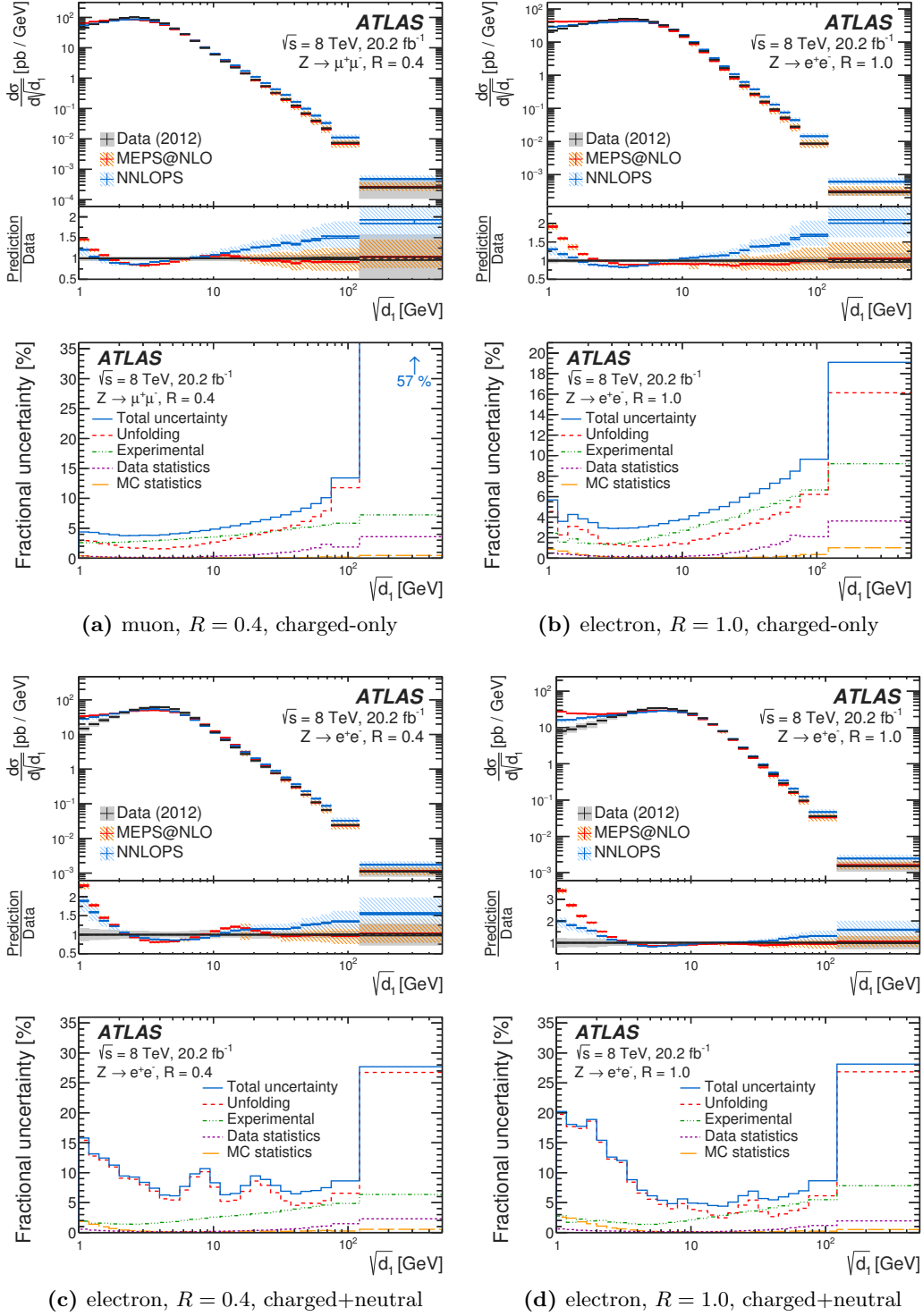
The uncertainties for the extrapolated charged+neutral distributions are increased due to the unfolding procedure, which includes the correction for going from a fiducial phase space using only charged particles to one using all particles. This effect is most significant for low values of the lower-order splitting scales such as  $\sqrt{d_1}$ , where uncertainties grow beyond 10% compared to less than 5% in the charged-only measurement. For higher values of the splitting scales the differences between the charged-only and charged+neutral uncertainties are not as large, as this region is not affected much by hadronisation effects. The peak of the extrapolated distributions, when compared to the nominal (charged) distributions, is shifted by roughly 1 GeV in the  $R = 0.4$  case and by about 2.5 GeV in the  $R = 1.0$  case. It moves to higher values of the splitting scales as expected given that the jet energies increase with the addition of neutral particles.

The two lepton flavours agree to better than  $1\sigma$ , once differences in the fiducial lepton selection are accounted for. The channels are not combined, because data statistics is a subdominant uncertainty. The  $R = 1.0$  comparisons reveal features similar to the  $R = 0.4$  case. A full set of distributions and systematic uncertainties in the  $R = 1.0$  case are shown in appendix A. Distributions of all possible combinations are furthermore provided in HEPDATA [54] along with an associated Rivet [55] routine.



**Figure 4.** Charged-only distributions for the eight leading splitting scales in the electron channel using the jet-radius parameter  $R = 0.4$ . The size of the error bars reflects the statistical uncertainty, while the combined statistical and systematic uncertainty is indicated by the grey band. Theoretical predictions from SHERPA with NLO multijet merging (“MEPS@NLO”) and from POWHEG+PYTHIA 8 with NNLO matching (“NNLOPS”) are displayed including error bands for the generator uncertainties.





**Figure 5.** Unfolded  $\sqrt{d_1}$  splitting scale for four different variations of the analysis as described in the sub-captions. The upper panels show the distributions in the same style as figure 4. The lower panels show breakdowns of the systematic uncertainties in data in the same style as figure 3.



## 7 Conclusions

Differential cross sections are measured as a function of the splitting scales in the  $k_t$  algorithm applied to the hadronic activity in  $Z \rightarrow \ell\ell$  events. The measurements use an 8 TeV proton-proton collision data set recorded by the ATLAS detector at the LHC with an integrated luminosity of  $20.2 \text{ fb}^{-1}$ .

Splitting scales up to the seventh order are measured for both the  $Z \rightarrow e^+e^-$  and  $Z \rightarrow \mu^+\mu^-$  channels and for jet-radius parameters of  $R = 0.4$  and  $R = 1.0$ . Charged-particle tracks are used for the analysis.

The measurements are corrected for detector effects. In addition to the charged-particle final state, a Monte Carlo simulation-based extrapolation to the charged- and neutral-particle final state is provided. The final results are compared to two state-of-the-art theoretical predictions, one including NNLO accuracy matrix elements, and a second prediction with multi-leg NLO merging. Significant deviations from data are found for both predictions, in the perturbative as well as the non-perturbative regimes.

The measurements of splitting scales are sensitive to the hard perturbative modelling at high scale values as well as soft hadronic activity at lower values. They thus provide a valuable input complementary to standard jet measurements, in particular in the transition region. With their specific identification of QCD jet evolution they provide means to constrain and potentially tune Monte Carlo event generators.

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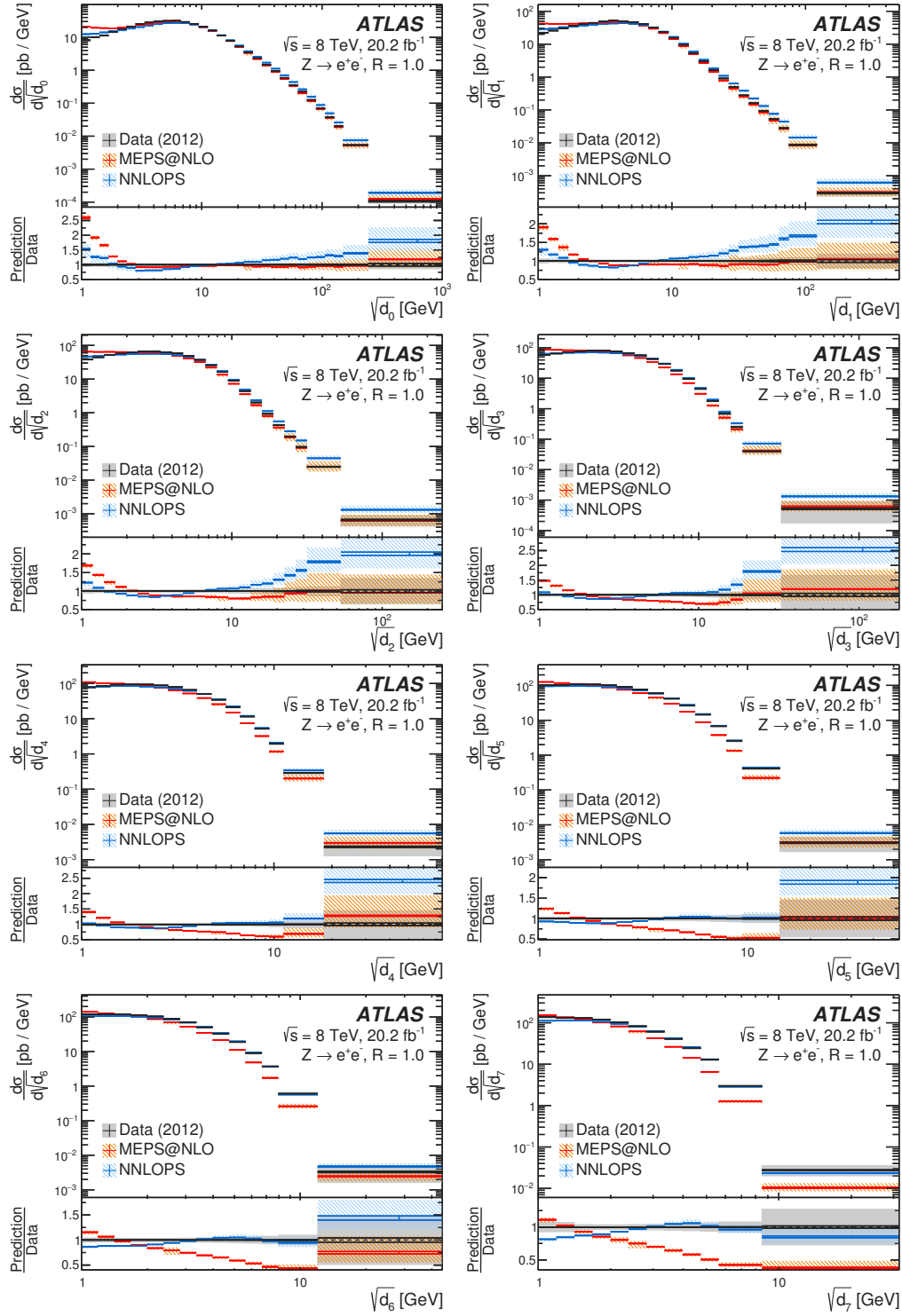
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## A Results for the electron channel with $R = 1.0$

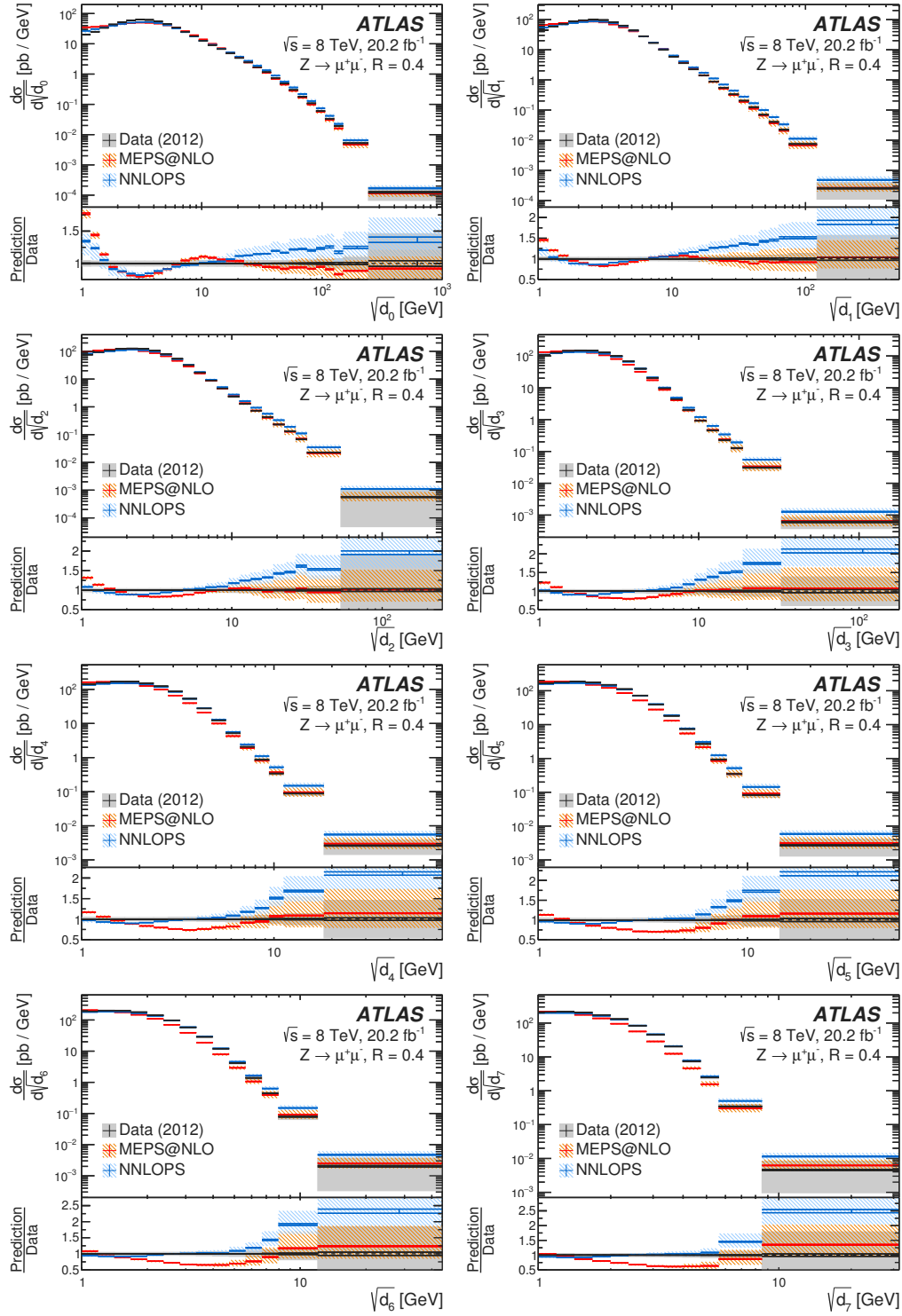
This section contains results obtained with a jet radius parameter  $R = 1.0$  in the electron channel.



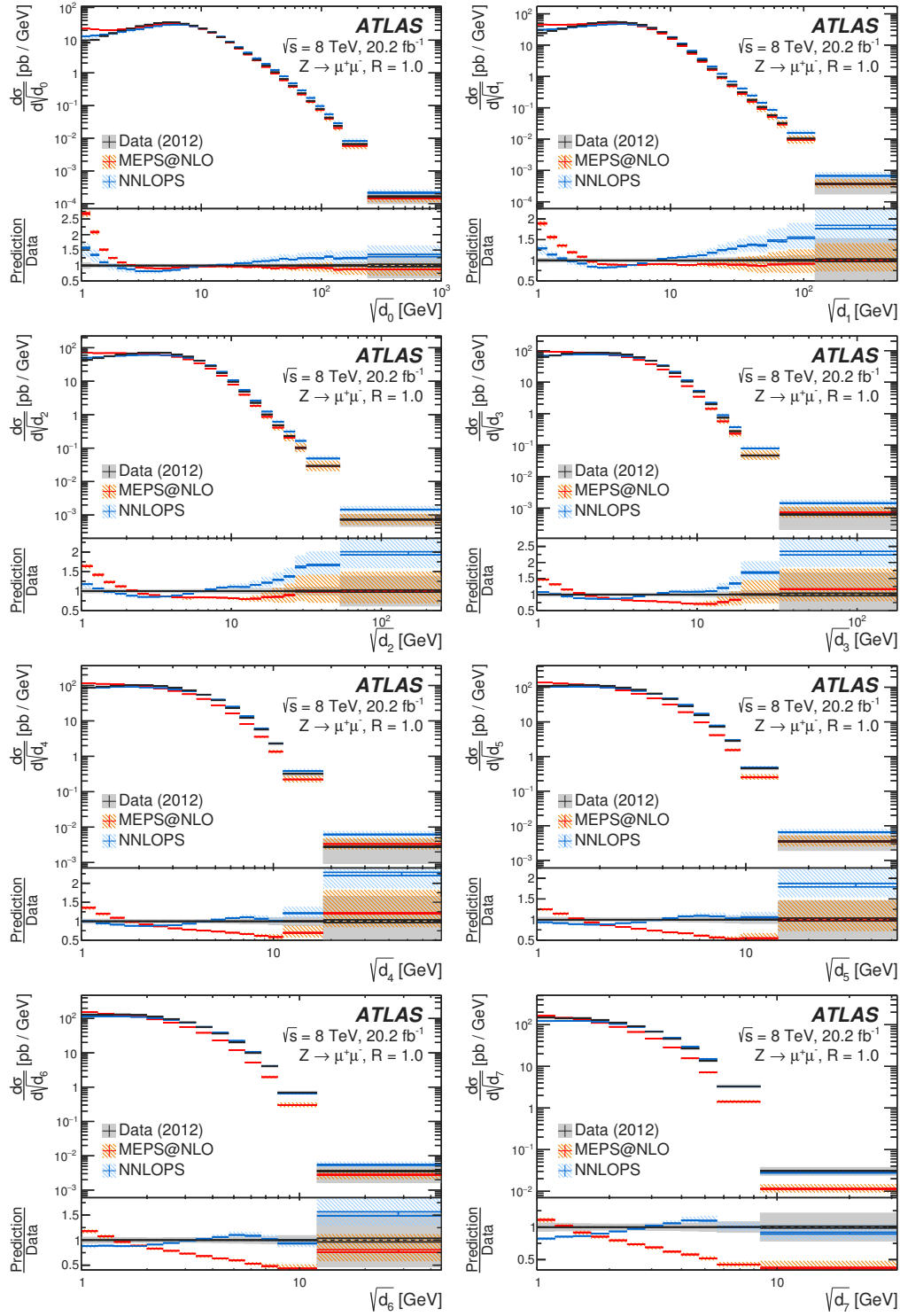
**Figure 6.** Charged-only distributions for the eight leading splitting scales in the electron channel using the jet-radius parameter  $R = 1.0$ . The size of the error bars reflects the statistical uncertainty, while the combined statistical and systematic uncertainty is indicated by the grey band. Theoretical predictions from SHERPA with NLO multijet merging (“MEPS@NLO”) and from POWHEG+PYTHIA 8 with NNLO matching (“NNLOPS”) are displayed.

## B Results for the muon channel with $R = 0.4$ and $R = 1.0$

This section contains results obtained with a jet-radius parameter  $R = 0.4$  and  $R = 1.0$  in the muon channel.



**Figure 7.** Charged-only distributions for the eight leading splitting scales in the muon channel using the jet-radius parameter  $R = 0.4$ . The size of the error bars reflects the statistical uncertainty, while the combined statistical and systematic uncertainty is indicated by the grey band. Theoretical predictions from SHERPA with NLO multijet merging (“MEPS@NLO”) and from POWHEG+PYTHIA 8 with NNLO matching (“NNLOPS”) are displayed.



**Figure 8.** Charged-only distributions for the eight leading splitting scales in the muon channel using the jet-radius parameter  $R = 1.0$ . The size of the error bars reflects the statistical uncertainty, while the combined statistical and systematic uncertainty is indicated by the grey band. Theoretical predictions from SHERPA with NLO multijet merging (“MEPS@NLO”) and from POWHEG+PYTHIA 8 with NNLO matching (“NNLOPS”) are displayed.

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## The ATLAS collaboration

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